

Field Quality Measurements of the LQXB Inner Triplet Quadrupoles for LHC

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Abstract As a part of the USLHC program, Fermilab is building half of the inner triplet quadrupole magnets for the LHC. Two identical quadrupoles (MQXB) with a dipole corrector between them in a single cryogenic unit (LQXB) comprise the Q2 optical element of the final focus triplets in the interaction regions. The 5.5 m long MQXB have a 70 mm aperture and operate in superfluid helium at 1.9 K with a peak field gradient of 215 T/m. Manufacturing of the 18 magnets is in an advanced stage. A program of magnetic field quality measurements of the magnets is performed at room temperature during magnet fabrication as well as at superfluid helium temperature during the cold qualification of each magnet. Results of the measurements are summarized in this paper.

Index Terms magnetic fields, quadrupole, superconductivity

I. INTRODUCTION

TO meet the high luminosity design specification (10^{34} cm⁻²s⁻¹) for the future Large Hadron Collider (LHC), special high gradient quadrupoles for the interaction regions are required [1]. These magnets, arranged as the final focus triplet Q1, Q2, Q3, shown in the schematic in Fig.1, have to provide a maximum operating gradient of 215 T/m at 1.9K in superfluid helium over a 70 mm coil bore due to a large variation of the β -function of the beam in the interaction regions. Half of these superconducting low-beta quadrupoles (MQXB) for the interaction regions are provided by Fermilab. The other half (MQXA) were produced by Toshiba in collaboration with KEK [2] and the final assembly, including the cryostating of all the magnets, is ongoing at Fermilab. To date, 15 of the cold MQXB masses have been built. Fourteen of them (MQXB01-12, 14,15), together with the corresponding correctors (MCBX), were selected for the assembly of the first seven LQXB01-07 cryogenic units. Six of them (LQXB01-06) have been cold tested; LQXB07 is currently undergoing testing.

The MQXB design, developed in collaboration with LBNL and BNL, is based on four two-layer coils connected in series.

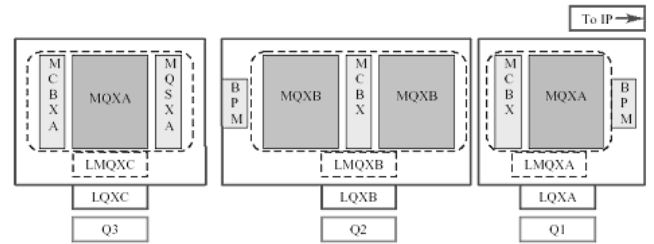


Fig. 1. Schematic of the LHC focusing inner triplet system. The LQXB magnet is the middle element in the triplet and consists of two MQXB quadrupoles.

The coils are surrounded by stainless steel collars and iron yoke laminations. Details of the MQXB design, changes and improvements during the initial test model program, are reported elsewhere [3]-[5].

In this paper we present the results of the production warm field measurements of MQXB01-15 in collared and yoked stages. The result from cold magnetic measurements are summarized and discussed as well.

II. MEASUREMENT SYSTEMS

Magnetic measurements were performed at the Fermilab's Magnet Test Facility. The field harmonics are measured with a rotating coil system that is integrated with a translation system, which is described below. Integral strength measurement is based on a Single Stretched Wire (SSW) system described in [6].

A. Measurement stands

Two similar horizontal stands were built for performing magnetic measurements. The stands utilize horizontal translation devices for positioning the rotating coil in the desired longitudinal (Z) position in a magnet. For in-process testing of the individual MQXB cold mass, a measurement stand with a 7.5 m stroke is used and for the final quality assurance magnetic measurements performed at superfluid (1.9 K) temperature, a stand with an 11.5 m stroke is used. The schematic sketch of the stands is presented in Fig. 2.

The rotating probe is connected to the drive system by a long drive shaft that is assembled from 1.5 m long sections. Included in each section is a bearing assembly and a flexible coupling. This shaft assembly is used to transfer the rotation

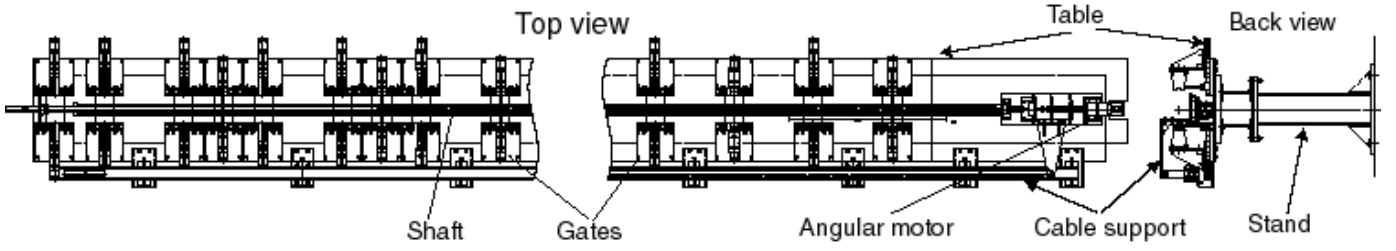


Fig. 2. Schematic view of the measurement stand

from the precisely controlled stepper motor to the probe. A 10:1 ratio gearbox is utilized as part of the probe drive assembly to smooth out the angular steps from the motor. The longitudinal positioning of the probe is achieved with the use of a motor and belt driven horizontal translation device, in conjunction with the cycling (open/close) of a set of support gates. The gates support the drive shaft against gravity, and they are spaced on the table, relative to the position of a flexible coupling and bearing in such a way as to have alternate gates in the open position at all times. At any given time, 50 percent of the gates are open while the rest are supporting the shaft assembly. The gates are controlled by photo-eyes and cycle open/close via pneumatic cylinders when a bearing assembly or flexible coupling which are larger in diameter than the shaft, approach the gate.

B. Measurement probes and DAQ system

Similar probes were utilized for the warm and cold magnetic measurements. They have a tangential winding for determination of higher order harmonics as well as two dipole and two quadrupole windings sensitive to the lowest order field components. The geometry of the probes is selected in a way that allows for bucking of the large low order field components in the tangential winding signal. Warm measurements for quality control during cold mass production are made with a coil of 31.8 mm nominal radius and of 0.91 m length. For the cold measurements two different probes were exploited. The integral harmonics are obtained using a 7.1 m long rotating coil with 41 mm nominal diameter assembled from three independent probes connected in series. In addition to the integral measurements a DC cold scan was done with an 81 cm long probe of 39.2 mm nominal diameter.

The DAQ system is based on five Metrolab 5035 PDIs reading the coil winding voltages. An HP3458 DVM is used to monitor the magnet current. PDIs and DVM are triggered by an angular encoder directly synchronizing the simultaneous measurements of field and current. To center the probe in the magnet a feed down technique of the off-centered quadrupole to the dipole field is applied.

III. FIELD ANALYSIS

All results are expressed according to the convention that the field is represented in terms of harmonics coefficients defined in a series expansion given by

$$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0} \right)^{n-1}$$

where B_x and B_y are the field components in the Cartesian coordinates, b_n and a_n are the $2n$ -pole normal and skew coefficients at the reference radius r_0 of 17 mm chosen for LHC ($b_2 = 10^4$). The coordinate system is defined in [7].

A. Results of the warm measurements

In the process of the production of each MQXB magnet, two measurements are performed to ensure magnet field quality. In the first one, an integral z-scan of the collared coil is executed. This measurement checks the quality of the coil assembly due to the collaring process. The second z-scan follows the yoking process. The rotating coil probe is placed at the same z-positions as for the collared coil measurements. This allows us to determine harmonic changes due to the addition of the yoke and the welding process.

Fig. 3 shows the integrated harmonics up to the dodecapole for the MQXB01-15 production cold masses (open and filled triangles for normal and skew harmonics respectively). The values are compared to the average of the last five magnets from the model program (open and filled circles, the error bars represent one sigma deviation) [2],[7] and to the full-scale prototype (open and filled diamonds) [8]. An acceptable but systematic deviation from the average harmonics of short model magnet tests is observed in the normal dodecapole for the first three cold masses MQXB01-03 (see Fig. 3 bottom right corner).

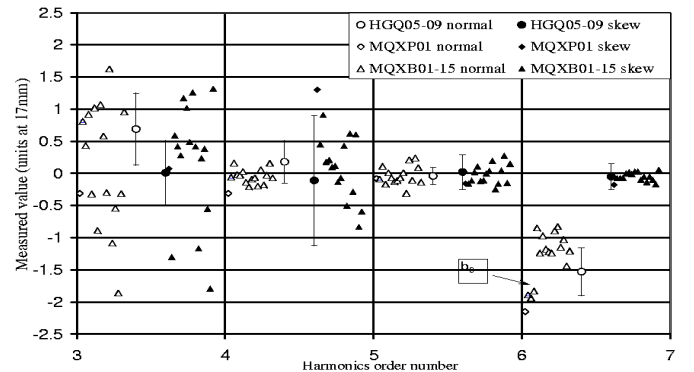


Fig. 3. Measured collared coil harmonics in the body of MQXB01 through MQXB15. The open and filled circles represent the average harmonics derived from the model magnet program. The error bars are one sigma. The arrow points at a systematically larger dodecapole for the prototype and the first three production cold masses.

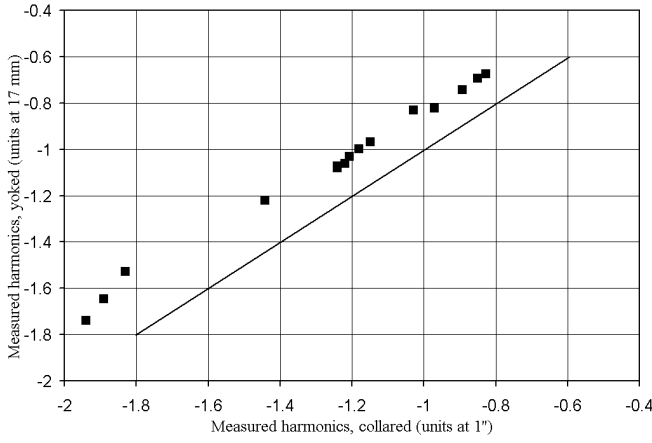


Fig. 4. Correlation between the normal dodecapole before and after process of cold mass yoking.

A similar result for b_6 is obtained for the yoked cold masses. The correlation between dodecapole measured before and after yoking is shown in Fig.4. The solid line corresponds to the case of no change in b_6 . There is an average decrease of 0.2 unit in the dodecapole b_6 after yoking. However, an accelerator simulation indicated that in some configurations b_6 could still be too large to be compensated with the available corrector strength. An effort was made in the production to decrease the normal dodecapole deviation. The result of the field calculation was implemented first in the MQXB04 cold mass. A new shim pattern in the coils was applied. Measurements of the collared coil showed a change of 1.2 units in b_6 , somewhat larger than the expected 0.8 units from the calculation. After additional tuning the coil shimming pattern was fixed for MQXB05 and the following cold masses. In detail the correction procedure is described in [9], [10].

B. Cold measurements

The final quality assurance magnetic measurements were performed at superfluid helium temperature ($\sim 1.9\text{K}$) on the MQXB cold masses assembled in cryogenic units LQXB01-06 (except for rejected LQXB02 assembly due to limited quench performance of MQXB04 [11]). The integral field harmonics at 11.9 kA (215 T/m), up to order 10, are presented in Fig 5. They are compared with the reference values from Table v.3.2

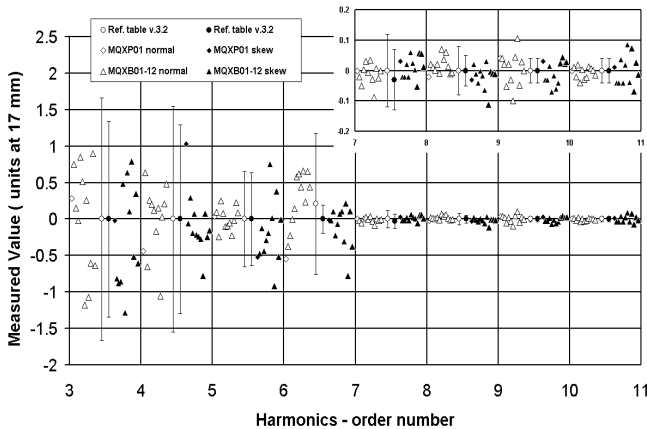


Fig. 5. Integral field harmonics (in units at 17 mm) in MQXB cold masses at 11.9 kA current (215 T/m) compared with the acceptance criteria defined in Ref. Table v.3.2 [3]. The inset shows the higher order harmonics.

TABLE I
INTEGRAL GRADIENT TRANSFER FUNCTION (T/kA)

Magnet	LHC operation	
	Injection (0.67 kA)	Collision (11.9 kA)
LQXB01	202.14 \pm 0.02	197.72 \pm 0.06
LQXB03	202.22 \pm 0.01	197.97 \pm 0.08
LQXB04	202.20 \pm 0.02	197.94 \pm 0.06
LQXB05	202.43 \pm 0.02	197.83 \pm 0.05
LQXB06	202.30 \pm 0.02	198.29 \pm 0.06
Average	202.26 \pm 0.01	197.94 \pm 0.03

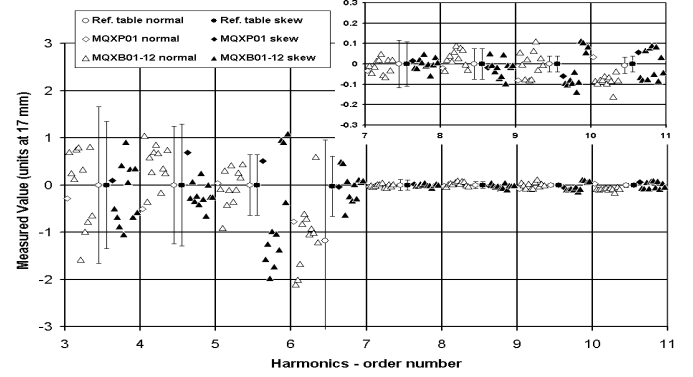


Fig. 6. Integral field harmonics (in units at 17 mm) in MQXB cold masses at 0.67 kA LHC injection current compared with the acceptance criteria defined in Ref. Table v.3.2. The inset shows the higher order harmonics.

[3] that were derived from the latter stage of the model magnet program. The errors assigned to the reference means (see Fig. 5 points with error bars), correspond to $\delta(b_{n,a_n}) = d(b_{n,a_n}) + 3\sigma(b_{n,a_n})$, where d and σ are the uncertainty in mean and standard deviation respectively. One may conclude that at the LHC operating current the low magnet harmonics are within limits. Some of the higher order harmonics ($b_{9,10}$ and $a_{9,10}$) are outside 3 sigma border. The r.m.s. of the measured central values is in the order of 0.03 units which may point into direction of a possible limitation of the measurement system.

The integral field harmonics at injections current 0.67 kA (12.3 T) are shown in Fig. 6. A deviation from $\pm\delta(a_5)$, skew decapole was observed. This deviation was found neither in the warm nor in the model magnet program measurements; this discrepancy diminishes at the collision current at 11.9 kA (see Fig. 5). Our current understanding of the problem points

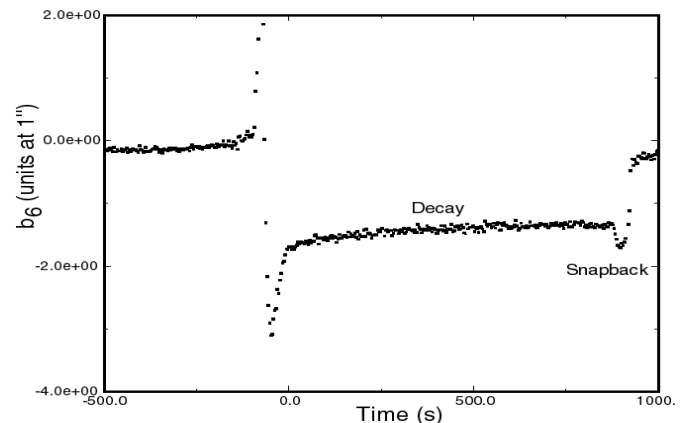


Fig. 7. An example of decay and snap-back of the dodecapole component for a plateau at injection of 900 s in MQXB11.

TABLE II
DECAY AMPLITUDE AND SNAPBACK TIME IN THE NORMAL DODECAPOLE

Cold mass	Decay Amplitude* (Units at 17 mm)	Decay Time (s)
MQXB01	0.47	12.4
MQXB02	0.34	8.4
MQXB05	0.48	15.9
MQXB06	0.48	14.3
MQXB07	0.28	10.1
MQXB08	0.24	7.9
MQXB09	0.32	9.1
MQXB12	0.33	8.7
Average	0.37	10.1

* After a subtraction of the underlying hysteresis loop

toward up-down asymmetry placement of the cold mass in the cryostat which might introduce the skew decapole. Additional checks and model calculations will be performed to confirm or reject this hypothesis.

The integral quadrupole gradient transfer function over the 11 m LQXB unit length (one LQXB contains two MQXB cold masses) was measured with SSW and the results are summarized in Table I. The average transfer function is found to be 202.26 ± 0.01 T/kA at injection (0.67 kA) and 197.94 ± 0.03 T/kA at collision (11.9 kA).

C. Decay and snapback

A well-known problem associated with the superconducting magnets is the decay and subsequent snap back of field components at the injection plateau. To characterize this effect in the MQXB quadrupoles, we performed measurements with an accelerator cycle similar to the one used in the LHC arc dipole tests. The duration of the plateau is 15 min at 0.67 kA (12.3 T/m). A typical example of the decay and snapback in MQXB11 is shown in Fig. 7. Table II summarizes the decay amplitude and snapback time for the measured MQXB. The decay and the snapback are parametrized with a logarithmic and gaussian functional forms described in [12]. The average decay amplitude is ~ 0.4 units after 900 s. followed by the snap-back time of ~ 10 s.

D. Eddy currents

Current loops at 40 and 80 A/s for MQXB quadrupoles have been executed. The difference between the different ramp rate loops was small, indicating small eddy current effects. Table III summarizes the width $\Delta b_6 = (b_6^{\text{up ramp}} - b_6^{\text{down ramp}})$ of the dodecapole hysteresis at 6.0 kA. The last row in the table averages Δb_6 for the model magnets 5 and 9 [3]. One can conclude that MQXB01-12 has a similar behavior to the model magnets and that the Eddy current contribution to b_6 hysteresis is rather small.

IV. CONCLUSION

Fifteen of a total of eighteen superconducting low-beta quadrupole cold masses for LHC have been produced. The quality assurance warm magnetic measurements after collaring and yoking of these cold masses are within specifications established by the last five short model magnets and the first full scale prototype [3], [7], [8].

TABLE III
HYSTERESIS WIDTH OF THE DODECAPOLE AT 6.0 kA

Cold mass	Δb_6^{40} at 40 A/s (Units at 17mm)	Δb_6^{80} at 80 A/s (Units at 17mm)	$\Delta b_6^{40} - \Delta b_6^{80}$
MQXB01	-0.60	-0.87	0.27
MQXB02	-0.45	-0.51	0.06
MQXB03	-0.24	-0.38	0.14
MQXB05	-0.28	-0.37	0.09
MQXB06	-0.21	-0.26	0.05
MQXB07	-0.13	-0.35	0.22
MQXB08	-0.19	-0.22	0.03
MQXB09	-0.21	-0.21	0.00
MQXB10	-0.35	-0.35	0.00
MQXB11	0.05	-0.13	0.18
MQXB12	-0.32	-0.42	0.10
Average	-0.27	-0.37	0.10
Model Program	-0.1	-0.35	0.25

Cold magnetic measurements were performed on the MQXB cold masses assembled in the LQXB cryogenic units. As a whole, at injection and collision, the integral field harmonics are quite small and they are consistent with the reference ones derived from the model magnet program. Some deviations are observed in higher level harmonics (order 9,10) and in the skew decapole at injection.

An additional study of dynamics effects was made at the injection plateau current. The decay and snap-back after 15min injection showed an average change in b_6 of ~ 0.4 units and consistent decay times of ~ 10.1 s. Eddy current effects leading to large ramp dependence in the allowed harmonics were not observed in the dodecapole hysteresis.

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